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# New Paradigms of Positive Safety and Human Error 3.0 Proposed for Advances of Human Factors Engineering in Nuclear

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## 1. Introduction

Renewed attention to human error has emerged amid rapid technological advances and heightened societal sensitivity to safety [3]. This paper criticizes prevailing definitions, taxonomies, and intervention strategies for human error and human factors engineering, arguing for a recent paradigm shift suitable for AI-intensive socio-technical systems. While human error has long been treated as a foundational concern, limitations have become pronounced in new-technology contexts: difficulty meeting high-reliability requirements, *hindsight* bias in *post-hoc* attributions, and side effects from local optimizations [5, 6, 9]. We reassess experiential patterns and conceptual boundaries of human error and comparatively review alternative frameworks - *Normal Accident*, *Safety II*, *Human Error 3.0*, and others, to identify viable paths beyond traditional approaches [11, 14, 17]. Typical analysis highlights four levers: reframing accidents as products of system interactions, engineering around constraints and feedback structures, treating success and failure as two sides of normal performance variability, and transitioning toward human-machine joint cognitive systems. It can be concluded by redirecting the focus of human error work from *post-hoc* labeling to proactive resilience building, aligning with a future-oriented human factors agenda that actively integrates emerging technologies.

## 2. Recent Trends on Human Error Safety - New Requirements on Safety

Due to the development of advanced technology and social changes, recent changes in safety and human error are required. The accountability of engineering for the completeness and exhaustiveness of technology, which have been traditionally maintained in the era of machines, has been fundamentally eased in the development of electronics, communication and computers. This is because realistic limitations on the completeness of software-based systems revealed in personal computers and related operating systems (OS) have been practically tolerated. The latest engineering technologies and related products experienced in laptops or smartphones are expected to operate (1) with a limited level of reliability and (2) with a limited performance that satisfies only the requirements (3) within a specific life cycle. If it does not work properly, the user is not un-familiar with re-booting or initializing. In addition, after a certain period, it is impossible to maintain expectations for initial performance, and even discarding before its lifespan has become frequent.

Nevertheless, the demand for technology and product safety has rather increased rapidly. Realistic safety related to technology and products must be achieved based on the functional reliability of the product. Therefore, it requires verification of the functional safety of technology and products and integrated maintenance over the life cycle, centering on IEC. Nevertheless, since most of the confirmation and verification of safety are post-mortem, complete verification is impossible or impractical. In addition, the phenomenon of guardianship is frequent, leading to controversy over personal errors and responsibilities of related persons. Most of the latest products have limited reliability and safety guarantees or are provided through separate additional contracts. The safety of the product has begun to be traded as a separate product (after-service and warranty, etc.) separately from the product, or as a kind of insurance for post-compensation.

In addition, in recent years, problems with specific products have revealed great social ramifications and influences. This is because it is inevitable that the characteristics of the latest electronic and communication technologies are connected in a social network and spread in a way that exceeds the intended level. Unlike in the past, problems with certain products and technologies can spread rapidly without remaining as independent problems. This can be called a "*super-connected*" characteristic, but it is not considered in advance in terms of the entire society, acting as a serious vulnerability. As a vulnerability, safety turns into human error and controversy over responsibility among stakeholders. In most cases, the responsibility for human error is ineffective because recovery to its original state or sufficient compensation is impossible.

Most new technologies take high reliability for granted, but they are basically changing beyond a rapid increase in safety demands. Although the uncertainty of safety has intensified due to the finiteness of technology and related verification, the safety needs of users and society have become stronger. This is because safety sensitivity has changed due to the hyper-connectivity of technology and its resulting vulnerability. It can be said that it is "*hyper-sensitive*" to the safety of technology.

Beyond injuries or direct losses, it has become related to the loss of utility from various perspectives. The greater the utility of the technology and the wider the ripple effect, the stronger the compensation for loss of utility and the guarantee of safety are required. It should be noted that awareness of safety has become diverse. Traditional safety has mostly been related to death or injury, and it has been about economic losses suffered in production and property. Therefore, traditional safety has been embodied as human and material losses expressed in economic value, or their possibility.

Safety is expressed as a risk, which is the magnitude of the expected possible loss, and minimizing risk was used as a specific target of safety management. However, there is a need for a plan to include subjective factors such as abstract value decline and rejection beyond objective injury or property loss as risks. The scope of safety has been greatly expanded in a way that considers not only the diversity of safety parties (stakeholders), but also time and situational changes.

## 3. A Brief Review of Human Errors in Conceptual Changes in Safety

As a conceptual change in safety, which is the basis of human error, changes in the perspective and approach of human error are also needed. First, additional considerations have arisen for risks that have traditionally represented safety. Risk should be converted to future value perceived by human (related stakeholders) rather than engineering absolute value based on practical effect. This is according to the results of research in behavioral science and behavioral economics that developed rapidly at the end of the 20th century. In addition, the safety concept extended to a *positive* dimension and changed into more practical safety is being discussed comparing to the negative concepts that minimize risks such as failure or loss.

### *3.1 Realization of Safety - More Realistic Risk*

Technologies related to safety decision-making have developed rapidly due to (quantitative) risks embodied in abstract safety. In particular, probabilistic risk assessment(PRA) developed as part of system safety has greatly contributed to safety in various fields by developing careful and effective techniques through efforts in the nuclear field. Today, PRA is adopted and spread as a technique representing probabilistic safety assessment (PSA). The risk (R), which means the expected loss representing safety, was obtained relatively simply. This is because it can be calculated as a dimensionless value by multiplying the magnitude of the loss and the probability (Risk = Loss x Prob.) occurring in a safety accident. During the past 20-th centuries, when safety has been quantitatively specified, the risk derived by multiplying loss by probability has been a key criterion and target of safety management. In order to manage and achieve safety more reasonably and systematically, it was possible to quantify risks and, based on this, comprehensively address safety issues in various fields and select specific decisions.

$$\textbf{Perceived Risk } (R') = f\left(\{u(\text{Loss})_i \times \pi(\text{Pro.})_j\}_k\right)$$

✓ $u(\text{Loss})_i$ = utility value of $\text{Loss}_i$
✓ $\pi(\text{Prob.})_j$ = weighted prob. of $\text{Pro}_j$
✓ $f(\text{Risk}_k)$ = integration of $\text{Risk}_k$

**'u' means utility function that might be convex for gain and concave for loss along the reference point selected by people in risk perceptions and decisions. 'ð' means decision weight that may be a typical s-shape curve of conservatism∫ means the integral of risks rather than simple additive calculation.**

However, significant changes in the quantification of risk, the core of safety decision-making, began at the end of the 20-th century. Human decision-making ultimately appears as a choice, cognitive psychological observations frequently showed completely different results from reasonably calculated risks and choices based on them. In particular, a number of studies on decision-making under uncertainty have confirmed that humans reveal various marginal characteristics and biases and use very harsh heuristics. The traditional "reasonable human" or so-called "**EON**" hypothesis for human decision-making has been denied. This has brought about major changes in the economic and financial sectors (demonstrated by repeated Nobel laureates in 1972, 2002, and 2016), and has serious implications for safety. As in the economic field, it has been found that it is difficult for humans to maintain objective/normative rationality according to the theoretically expected rationality even in safety-related decision-making. Individuality and sensitivity to safety have increased, making it even more difficult. [6,7,14]

This means a fundamental change in the process of quantifying risk. First of all, since the risk is quantified by the magnitude of the expected (reasonable) expected loss, the magnitude and probability of the loss should be converted into a subjective perception and prospect value of loss and probability, not objective past performance data. Traditional engineering leak (R) presented loss and probability as figures through objective performance or output data. However, the true risk (R*) should not be fundamentally an objective number, but a future value that reflects this in decision-making and action. This is because it is not a past but a future expected or predicted value.

Transform functions should be applied to convert losses and probabilities reflected in engineering risks into future values. A representative function that changes an objective value into a realistic value is a utility function, but at least it is not simple linear. The utility function is out of line and is mostly identified as an S-curve. This is because it typically reveals conservatism or sensitivity in two extreme areas, such as minimum or maximum. This is similar not only in loss values but also in absolute functions that convert probability into realistic possibility. The quantification of Leaks, representing more realistic safety, can obtain support for practical calculation methodologies simply illustrated below through the development of behavioral science and behavioral economics.

However, the fundamental characteristics of human perception of safety provided by behavioral economics and behavioral science are not simple, so considerable attention will be required for each specific topic[14]. Among them, the limitation that various values included in safety may not be easily integrated in human decision-making related to safety (such as the so-called different mental account phenomenon) requires additional attention and research. This means that a more careful approach is needed in safety fields that are sensitive to socially diverse groups, such as nuclear safety. On the other hand, Nudge, which is in the spotlight as a highly effective technique for promoting safety decision-making, will be an important technology and development task in securing the possibility of positive promotion in safety decision.

***3.2*** *Conceptual Extensions for More Substantial Safety - from Negative Safety to Positive Safety*

As shown in the conceptual definition of safety (IEC-std 4 & 57) such as "Freedom from Harm & Hazards", safety was represented as a negative aspect only. Traditionally, negative problems such as failures, accidents, and losses, and minimizing risks that indicate such possibilities have been equated with safety. In practice, minimization of quantitative risks representing risk has been regarded as the same as maximization of safety. Risk has been treated as a substance of safety.[9]

However, minimizing risks and risks and eliminating defects and problems do not mean maximizing safety. Apart from eliminating problems such as defects and failures, there is a new way to make them work safely, and additional ways to maintain safety can also be developed. In the 21st century, discussions on resilience have had a great impact on the safety field, and are already being actively discussed as *Safety II*.

The concept of Safety II can also be effectively applied to human errors in the view that the overall failure has occurred due to a failure or defect in any part does not mean that it will cause immediate loss. If no action is needed, even if it is a failure, it may not be an accident or human error that violates safety. In addition, apart from minimizing defects and problems, there are a variety of additional ways to improve safety, and prevention and improvement of human errors have the same meaning.

Although the functional reliability of predefined functions is an important criterion for estimating the safety of a system, identifying them as safety is conceptually a wrong limitation. Resilience or resilience to restore a problem and failure to a normal state before it is realized as a loss is a very important safety. This is because even in the process of failure resulting in loss, a fundamental difference in safety level can be obtained if appropriate countermeasures and resilience are secured to offset the loss.

The expanded range of positive safety not only prevents risks, such as fundamentally possible (or expected) failures and problems from a negative perspective, but also a positive perspective of further defining, creating, or maximizing safety. In addition to the negative safety concept from a perspective that minimizes traditional problems, this implies the possibility and necessity of transitioning to a positive safety concept that adds to the maximization and obtainable utility of realistic success.

These positive perspectives have already been fully realized on safety that is realized in reality. For example, apart from functional safety that maximizes engineering reliability, the development of various active safety values or the addition of safety as a proactive countermeasure has already become commonplace in various cases. This can be presented as a tentatively named "Safety III", and examples of positive safety within the scope discussed so far can be presented as items for each detailed type as follows.

* ***S3.1 Surplus/Static Safety***
* ***S3.2 Effortive/Dynamic Safety***
* ***S3.3 Additive/Challenge Safety***

If traditional safety is expressed as zero-fault safety to minimize failures and problems, there could be other kinds of safety that additionally strengthens over the functional and zero-fault safety. At least are followings First, there is *surplus/static* safety. Securing *surplus to excess* safety that exceeds the standard required for the expected function does not add to functional safety, but has a great impact on the safety that is actually realized. This is because, compared to daily life, it is obvious that much more income gives a greater and clearer sense of safety than satisfying the minimum cost of living standards. Second, there is active/dynamic safety. Safety that actively offsets or recovers losses and damages when they occur is also an important positive safety. Apart from functional reliability, there is another *positive safety* that is realized in possible resilience, warranty, insurgency, and after-service. Third, finally, there is *additive/ challenge* safety. There is a safety that develops new risks that do not exist at present and provides them with additional utility. In the case of high-rise observation decks, sky-walks, and zip-line, it is an additional example of positive safety because it is created with new safety values by intentionally adding risks. It can be said that it is a clear additional safety if sufficient safety is guaranteed even though high-rise apartments clearly have a greater physical risk compared to the lower floors.

These additional items and technical developments of positive safety have significant implications for actively capturing a safe future from a broader perspective, away from the traditional perspective that has regarded human error as an object of minimizing negative defects and problems. If the safety of a ship is based on the premise of sailing into a storm rather than assuming it is anchored at a port, the fundamentally preset magnitude of the human error risk should be reflected in the magnitude of safety.

## 4. Extensions of the Concept of Human Error

***4.1** Perspectives on human errors - Addition of the concept of Human Error 3.0 [12,19]*

Human error means human failure. Since humans are beings that can fail, some degree of human error is considered inevitable. Cases in which generosity to human error is not allowed were limited to cases that were not intentional (mainly expressed by slip, lapse and mistake), and it was the traditional view that intentional errors such as violations and sabotages were not included in the scope of human error. However, it was because of the situation of the Industrial Revolution that this partially tolerant view of human error collapsed. In particular, human error in the role given to human workers (i.e., job task error) meant enormous losses in the process of mass production.

In the early days when ergonomics began in earnest, human error was literally *'an error of human'*. In order to prevent human error that may occur in the process of performing tasks and actions, early ergonomics developed *time-and-motion* research and various task management technologies for performance management. In order to maximize the job performance ability as a worker, job design that can minimize behavioral errors as well as education and training, motivation, and procedure development were active. For convenience, these early efforts and technologies of ergonomics can be distinguished as *Human Error 1.0*. The perspective of human error greatly contributed to the success of the early industrial revolution, called the scientific management and division of labor revolution, and exerted the effect of ergonomics without regret.

It was a natural result of the development of technology and machinery that fundamental changes in the concept of *Human Error 1.0* in ergonomics began early. This is because the development of machines has initiated a major change in the job of human workers, and various new manipulations and roles have been given to human. Human had to use a variety of tools and manipulators because of the diversity of roles given. The human role required to use the machine in charge of basic power and operation has become physically convenient, but there was a new problem. It caused a new human error in that the job had to be performed in a fragmented intermediate intervention method through indirect means. It turned out that the seriousness of human errors revealed in the actual use of high-performance fighter and ICMB's developed in the war was serious, accounting for 70-90% of the total problem. (This was later also applied to nuclear power plants, signaling that the proportion of human errors to the total risk was serious (1976 WASH-1400, etc.). However, the nuclear field did not actively accept ergonomics until such a notice was revealed, so we had to bear a shocking burden through the TMI nuclear accident.)

In human factors, this changed human error problem was diagnosed as a compatibility problem necessary for human-machine interaction. By accelerating the research and development of interfaces that provide human-machine interaction, the era of the tentatively named "*Human Error 2.0*" was opened. (Faced with the fact that the key cause of the TMI nuclear accident was human error in the nuclear, various follow-up measures were set up to prevent human error in the interaction of the operator. Mainly, it was to improve the procedural and control room interfaces and to provide additional well-organized interfaces such as the Safety Parameters Display System (SPDS). However, these fragmentary follow-up measures alone could not sufficiently overcome the reality of being shocked by the belief in safety. Therefore, the new notion of Man-Machine Interface System (MMIS) that could solve the human error problem of the interface fundamentally was proposed as a key requirement for future reactors jointly proposed by power providers. The MMIS concept contributed to raising the realistic level of nuclear safety faced by the TMI nuclear accident to an acceptable level. In the late 1980's, when the concept of MMIS was presented, Korea began to become independent in nuclear power plant technology, achieved the latest design reflecting the concept of MMIS, and was able to compete for exports.)

Today's human error is not simply a literal "error of human". Rather, it can be called "error of human factors", which is a problem and defects in surrounding factors that cause errors in humans. Human error research has shifted to the perspective of studying human factors and their effects. (In that sense, the empirical approach to the error probability of the job unit in the quantitative study of human error seems to be excessive or fundamentally inappropriate.)

Human error 2.0 technology (coincidentally, in the nuclear field that opened the era of human error 2.0) is facing new challenges. This is because it began with the Chernobyl nuclear accident that occurred in 1986 and turned out to be a new cause of unavoidable catastrophic uncertainty in the Fukushima nuclear accident in 2011. The close review and reflection of the Chernobyl and Fukushima nuclear power plant accidents are consequently concentrated into a safety culture, which can be called human error in a broad sense, in a new dimension. The safety culture will be one of the most frequent and important safety challenges raised in fields other than nuclear today. (In the frequent discussion of safety culture, the following error attribution phenomenon is accelerating. It was separately pointed out that safety culture is incorrectly used as (1) *causality* as a cause in the analysis of human error, (2) *convenience* as a termination criterion for complex analysis, and (3) *artificiality* in selection of countermeasures. (2018 Lee Y.H.) [12,13]

***4.2** Additional Concept of Human Error 3.0*

Even though the concepts of *Human Error 1.0 and 2.0* are spreading, the development of human error technology suitable for the safety required by the development of new technologies is insufficient. In order to cope with the problem of human error raised as a new dimension, the notional new concept of *Human Error 3.0* was proposed as follows in terms of (1) irresponsible/effective safety (2) ultimate responsibility for the safety of the entire system.

The recent safety cases that have led to unfortunate loss of life reveal a fundamental problem that is difficult to be satisfied with the traditional human error perspective. The so-called "*structured irresponsibility*" problem of transferring the responsibility for the behavior and loss of a huge system to the practitioners in charge of the tasks segmented into an out-of-the-loop state that cannot know or manage the behavior of the entire system is unscrupulous beyond simple irrationality. In today's reality, which is formed by a very complex structure as well as various internal and external relations structures, the issue of how the vulnerabilities or risks of a given system are given to practitioners at the sharp end is an important topic. Human engineering, which ensures the optimization of the system, should not unfairly shift responsibility for hidden risks or make mistakes.

High quality/high reliability and functional safety alone in individual parts cannot guarantee the safety of the entire system. (MIT Professor C. Perrow suggested the concept of "*Normal Accident*" that, as a conclusion of the TMI nuclear accident analysis, the fundamental vulnerability of a large system consisting of millions of parts could occur even if there were no defects individually. In addition, in the field of sociology, Professor U. Beck has proposed the *Risk Society Paradigm*, which promotes attention to the fundamental imperfections of society.) Even if the system is composed of perfectly safe parts, the final safety that a large number of parts gather and reveal is different. In particular, despite great effort being put into the design configuration of the system, safety can fundamentally change in realistic operation due to the accumulation and diffusion of uncertainty. [9, 11]

Second, given technological and social changes, it is inevitable to look for the ultimate role of human error for safety because all accidents can be called human error in a broad sense. Disasters that were accepted as unavoidable fate in the past, such as natural disasters, are now turning into important safety tasks in terms of the possibility of minimizing their ripple losses. Even natural disasters such as floods, typhoons, and earthquakes are discussed as human-made because technical possibilities needed in the future can be found, not to hold them accountable for the losses that have already occurred.[7] It is intended to include the recognition and necessity of the possibility of pre- and post-effort efforts for the future through the perspective of human error. Even if it is a fundamentally inevitable natural disaster, the reality and losses that are ultimately given may be regrettable because we ultimately have to take responsibility for and deal with them. Therefore, from the perspective of human ultimate responsibility, find future countermeasures through *Human Error 3.0*. [11]

Rather than clinging to partial accountability in the past, it is trying to find the possibility of improvement in the future. Even if human error did not cause the accidents and losses, there is a possibility of preparing for it through some human factors viewed as a problem of human error. Rather than limiting the R&D goal of human error to simply to functionally achieve a given task (traditional negative safety), it should be expanded with technology that can actively develop additional safety possibilities (such as *S3.1 ~ 3.3* exemplified above). The concept of *human error 3.0* emphasizes that we must deviate from the traditional perspective in the process of human error investigation. In particular, we must escape the myth of objective cause or responsibility identification. It should be shifted to a perspective of countermeasures that are practically possible. Rather than sticking to the investigation to objective cause in human error-related accidents that have already occurred, it seeks future-oriented possibilities to secure and promote additional safety.

*Human Error 3.0* emphasizes a more active perspective, including violation and sabotage. This is because they are free from the burden of identifying responsibilities related to human errors and seek technical possibilities. In addition, in order to further develop active safety in a way that challenges various new risks, we look for the possibility of further development of positive safety that overcomes new human errors suggested by artificial intelligence. It is possible to actively develop additional safety through human errors such as interest, challenge, and reward. This possibility of securing additional safety can be achieved through an emergent process of considering and devising the possibility of changes reflecting new technologies and perspectives beyond past performance or existing settings.

### *4.3. Human Error 3.0 and Positive Safety*

Recently, newly proposed paradigms for safety have been actively discussed. In addition to the previously proposed *Normal Accident*, recent *STAMP*, *Safety II* are causing drastic changes in the perspective and approach of safety and human error. Since human error consists of interactions with machines and technologies, it would be reasonable to be captured in a wider range and various movements including positive aspects of safety too. However, traditionally, there is still a limit to seeing human error as a limited structure or a fixed mechanism of related factors. This is limited in that the ultimate realization of human error is left to human.

In that respect, the concept that the IAEA and others are highlighting in the Fukushima accident investigation report is very important [3]. For example, consideration of *unknown-unknown* (error/risk) and preparation for *un prepared -ness* can be cited. The future of human error research must include an open perspective to include such possibilities that are not yet detected. *Human Error 3.0* is a concept proposed to practically include the possibility of search in future beyond a retrospective approach based on the past faults and defects. (Especially in human error investigation and analysis, the focus is on deriving future countermeasures rather than past causes that could be scientifically true.)

Similar to the perspective of a preset structure in the early or design of the system, explaining or approaching human error as a "*systemic perspective*" can technically limit the capture of various and infinite possibilities of human error as a behavior that humans can take in the future. In addition, excessive mechanical efforts set up for the application of techniques applying a systematic perspective also raise burdens and some questions about the practical applicability of the proposed technology. This is because the vast detailed elements and complex analytical procedures and models found *in Safety II and STAMP* are reluctant from the beginning in terms of the realistic practical burden required for the study of human error at hand. Therefore, an open perspective should be maintained practically by conducting the future of human error. An extended perspective such as *Human Error 3.0 and Positive Safety proposed in this paper* can be said to be effective in seeking open possibilities that do not stick to the limitations of structuralism perspective or reductionism approaches.

## 5. Conclusions and Discussions

With the development of new technologies and societal progress, safety changes itself rapidly, and interest in human errors is rapidly taking place. In this paper, the traditional concept and approach of human error was reviewed, and the direction of human error research and development according to the conceptual change and expansion of safety was discussed. In the case of ergonomically applying a new technology represented by artificial intelligence, it may not be optimal to simply reduce the burden in place of human duties and roles, or rather face new problems. Human error is no longer just an error of human and requires a new perspective. It must go beyond the traditional reduction approach to focus on defects and problems in specific parts or elements. It should be able to effectively deal with configurations that can be revealed in the realistic operation of the entire system and interactions with various possibilities that may occur in the future.

First of all, beyond the negative limited perspective such as risk minimization traditionally adopted, the positive safety concept necessary for the realization and expansion of safety can be adopted and an expanded concept and paradigm can be applied. [6, 18]

As discussed above, *Human Error 3.0 and* real safety (S*) including *positive safety* might realize more realistically nuclear safety in practice. In order to meet new safety needs and perspectives in human factors, it will be possible to explore more diverse possibilities for active expansion of technical safety by applying the new concept of *Positive Safety* and *Human Error 3.0.* In a broad sense, it could be a new technical addition to the traditional engineering works with a perspective of human error and human factors. The conceptual expansion of safety and human error reviewed in this paper can contribute to driving a new and clear safety future in nuclear. [19]

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